Parametric study on abrasion wear of compounds

W. Bryan Holwell, Bin Chung, Glenn Denstaedt and Roger Luo
Maxxis/Cheng Shin Tire USA

Perhaps the largest factor influencing the tread life of a tire is the resistance to abrasive wear of the tread compound.

Many types of abrasion machines have been utilized in the lab to test the wear rate of tread compounds in order to provide insight into the performance of a compound before performing costly and time-consuming field tests.

This study takes an in-depth look at the abrasion wear of rubber compounds using the Ueshima AB-2010 FPS Wear Testing System (Figs. 1 and 2).

This piece of equipment is a sophisticated Lambourn-type abrader that can automatically test up to 50 samples continuously.

The variable test parameters include the sample wheel speed (0-999 RPM), drum wheel speed (0-200 RPM), slip rate (1-20 percent), load (5-80 N), slip angle (-5 to 5 degrees), test temperature (RT - 60° C) and talc flow rate (0-0.782 cc/min).

Parametric studies were conducted to determine what effects, if any, varying these parameters had on the linear wear rate and the abrasion energy of the tested compound.

Linear wear rate

The linear wear rate is the thickness of rubber that is abraded away (in millimeters) per 1,000 km of distance traveled. This data is automatically calculated by the Ueshima test system using Equation 1.

\[ W = \frac{(Fy - Fo) \times (\text{Slip\_ratio} \%) \times \pi}{Sd (\text{mm}) \times Sw (\text{mm})} \]

Equation 1. Linear wear rate.

Equation 2. Abrasion energy.

Abrasion energy

The abrasion energy is also calculated automatically by the equipment using Equation 2.

\[ A = K \times (\epsilon W)^{(n-f)} \]

Equation 3. Abradability.


\[ V = \frac{\Delta W (g) \times (1000 \times 60)}{\text{time (sec)} \times D (g/ cm^3) \times S (\text{mm}) \times Sw (\text{mm}) \times Da (\text{mm}) \times Dr (\text{rpm}) \times \pi} \]

Equation 5. Silica compound.

\[ V = 1.77 (SR)^2 + 0.62 (SR)(L) - 2.69 (L) - 17.54 (SR) 
\quad + 71.54 
\quad (R^2 = 0.98) \]

Fig. 1. The Ueshima AB-2010 FPS wear tester, computer interface and dust collector.

Fig. 2. Internal view of the Ueshima AB-2010 FPS wear tester.

Fig. 3. Linear wear rate at multiple slip rates for different compounds.

Fig. 4. Abrasion energy at multiple slip rates for different compounds.

The linear wear rate of any tested compound may be dependent on certain test conditions, yet precise data can be recorded resulting in good relative rankings for the conditions tested.

A sample graph of the linear wear rate plotted against slip rate may be seen in Fig. 3.

Abrasion energy

The abrasion energy is also calculated automatically by the equipment using Equation 2.
Equation 6. Carbon black.

\[ eW = 2.087 \times 10^7 (L) + 1.861 \times 10^7 (SR) - 1.332 \times 10^7 \]

\[ [R^2 = 0.97] \]

Equation 7. Silica compound.

Silica Compound \[ eW = 2.232 \times 10^7 (L) + 1.833 \times 10^7 (SR) - 1.234 \times 10^7 \]

\[ [R^2 = 0.97] \]

Fig. 5. Log of abrasion energy plotted against log of linear wear rate.

Fig. 6. The effects of slip rate, slip angle, load and talc flow on volume loss, \( F_y \) and abrasion energy in the carbon black compound.

Fig. 7. The effects of talc flow, slip rate and load on volume loss, \( F_y \) and abrasion energy in the silica compound.

The abradability of a material is its relationship between the abrasion energy and the rate at which it abrades. See Abrasion, page 16

Table III. Compound formula of natural rubber compound (full antioxidant levels) used in high temperature testing.

<table>
<thead>
<tr>
<th>Materials</th>
<th>NR (SMR20CV60)</th>
<th>N234</th>
<th>Sunden 790</th>
<th>Structol 40MS</th>
<th>ZNO</th>
<th>SA</th>
<th>TMQ</th>
<th>6PPD</th>
<th>WAX</th>
<th>CTP</th>
<th>TBBS</th>
<th>Sulfur</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR</td>
<td>100</td>
<td>60</td>
<td>12</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>1.5</td>
<td>1.5</td>
<td>2</td>
<td>0.1</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>N234</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sunden 790</td>
<td>1.3</td>
<td>14</td>
<td>15</td>
<td>1.5</td>
<td>0.75</td>
<td>0</td>
<td>0.5</td>
<td>0.75</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Structol 40MS</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>ZNO</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>SA</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>TMQ</td>
<td>1.5</td>
<td>0.75</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0.75</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>6PPD</td>
<td>1.5</td>
<td>0.75</td>
<td>0</td>
<td>0.75</td>
<td>0</td>
<td>0</td>
<td>0.5</td>
<td>0.75</td>
<td>0</td>
<td>0.1</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>WAX</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>CTP</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>TBBS</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table IV. The formulas of the NR compounds used in the antioxidant study.

<table>
<thead>
<tr>
<th>Formula</th>
<th>( k )</th>
</tr>
</thead>
<tbody>
<tr>
<td>NR (SMR20CV60)</td>
<td>100</td>
</tr>
<tr>
<td>N234</td>
<td>60</td>
</tr>
<tr>
<td>Sunden 790</td>
<td>13</td>
</tr>
<tr>
<td>Structol 40MS</td>
<td>2</td>
</tr>
<tr>
<td>ZNO</td>
<td>4</td>
</tr>
<tr>
<td>SA</td>
<td>2</td>
</tr>
<tr>
<td>TMQ</td>
<td>1.5</td>
</tr>
<tr>
<td>6PPD</td>
<td>1.5</td>
</tr>
<tr>
<td>WAX</td>
<td>2</td>
</tr>
<tr>
<td>CTP</td>
<td>0.3</td>
</tr>
<tr>
<td>TBBS</td>
<td>1.5</td>
</tr>
<tr>
<td>Sulfur</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Table II. Conditions tested during the wheel speed study.

<table>
<thead>
<tr>
<th>Slip Rate</th>
<th>RPM-Drum</th>
<th>RPM-Sample</th>
<th>RPM-Drum</th>
<th>RPM-Sample</th>
<th>RPM-Drum</th>
<th>RPM-Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>-20%</td>
<td>200</td>
<td>799</td>
<td>150</td>
<td>599</td>
<td>100</td>
<td>400</td>
</tr>
<tr>
<td>-15%</td>
<td>200</td>
<td>849</td>
<td>150</td>
<td>637</td>
<td>100</td>
<td>424</td>
</tr>
<tr>
<td>-10%</td>
<td>200</td>
<td>899</td>
<td>150</td>
<td>674</td>
<td>100</td>
<td>449</td>
</tr>
<tr>
<td>-5%</td>
<td>200</td>
<td>949</td>
<td>150</td>
<td>712</td>
<td>100</td>
<td>474</td>
</tr>
<tr>
<td>0%</td>
<td>200</td>
<td>999</td>
<td>150</td>
<td>749</td>
<td>100</td>
<td>499</td>
</tr>
<tr>
<td>5%</td>
<td>191</td>
<td>999</td>
<td>149</td>
<td>749</td>
<td>95</td>
<td>499</td>
</tr>
<tr>
<td>10%</td>
<td>182</td>
<td>999</td>
<td>136</td>
<td>749</td>
<td>91</td>
<td>499</td>
</tr>
<tr>
<td>15%</td>
<td>174</td>
<td>999</td>
<td>130</td>
<td>749</td>
<td>87</td>
<td>499</td>
</tr>
<tr>
<td>20%</td>
<td>167</td>
<td>999</td>
<td>125</td>
<td>749</td>
<td>83</td>
<td>499</td>
</tr>
</tbody>
</table>
Abrasion

Continued from page 15

In a hard solid, it is simply the wear rate divided by the abrasion energy (V/W). In an elastomer, the wear rate is given by the formula V = K(W)^n, and the abradability is given by Equation 3.

Equation 6. Regression equation.

\[ V = 4.56(SR)^2 - 45.78(SR) + 0.33T + 109.93 \quad [R^2 = 0.99] \]

Fig. 8. The effect of load and slip rate on linear wear rate for carbon black compound.

Experimental Carbon black parametric study

A Solution Styrene Butadiene – Butadiene Rubber (SSBR-BR) compound formula consisting of 72 phr N234 carbon black and 8.7 phr oil was mixed for this study (Table 1). Additive and curative levels were adjusted based on the filler system used and industry recommendations. The tested parameters include slip rate (5 percent, 10 percent and 15 percent), load (25N, 35N and 45N), slip angle (0°, -2.5° and 5°) and talc flow rate.

Equation 9. Regression equation.

\[ (120 \text{ Grit}) \quad V = 2.68(SR)^2 + 0.92(L)(SR) - 51.39(SR) - 6.73(L) + 257.23 \quad [R^2 = 0.99] \]

Equation 10. Regression equation.

\[ (240 \text{ Grit}) \quad V = 1.52(SR)^2 + 0.50(L)(SR) - 32.14(SR) - 2.96(L) + 135.90 \quad [R^2 = 0.96] \]

Equation 11. Regression equation.

\[ (120 \text{ Grit}) \quad eW = 2.87(x10^3)(SR)^3 + 4.1x10^3(L)(SR)^2 - 2.3x10^4(SR)^2 + 0.0x10^6(L) + 2.57x10^3 \quad [R^2 = 0.98] \]

Equation 12. Regression equation.

\[ (240 \text{ Grit}) \quad eW = 4.96(x10^5)(SR)^2 + 2.26x10^2(L)(SR) - 8.0x10^2(SR)^2 + 0.0x10^4(L) + 3.91x10^3 \quad [R^2 = 0.99] \]

Fig. 10. The effect of load and slip rate on abrasion energy in the carbon black compound.

Fig. 11. The effect of load and slip rate on abrasion energy in the silica compound.

Fig. 12. Log V vs. Log eW for carbon black and silica compounds.
Silica parametric study
A Solution Styrene Butadiene Rubber compound formula consisting of 80 phr Hi-Sil 150 and 37.5 phr oil was mixed.

The order of the testing was randomized by the Stat-Ease Design Expert 7 software to ensure data repeatability and test the regression equations.

Wheel speed study
The same SSBR-BR carbon black compound was used in this study (Table I).

The applied rate of slip had a very strong effect on linear wear rate on both the carbon black and silica compounds tested (Fig. 6 and Fig. 7).

Both compounds exhibit accelerated wear at higher slip rates, as shown by their respective quadratic regression equations.

Rubber & Plastics News  ●  July 23, 2012  ●  17
The tested silica compound shows a higher rate of wear at higher slip rates compared to the carbon black compound. The load that is applied to the test sample during testing also shows to have a significant effect on linear wear rate. The effect is linear in nature for both the carbon black and the silica compounds, indicating a direct relationship between the applied load and the wear rate for the conditions tested, as shown by Equations 4 and 5, where V is Linear Wear Rate, SR is Slip Rate, and L is Load. The graphs of these equations may be seen in Fig. 8 and Fig. 9.

Effect of slip rate and load on abrasion energy
Varying the slip rate also proves to have a significant effect on the recorded abrasion energy of both the carbon black and silica compounds (Fig. 6 and Fig. 7). Their respective regression equations (Equations 6 and 7) are much more linear than those for linear wear rate, suggesting a more direct relationship. The applied load also strongly affects the recorded abrasion energy for both the carbon black and silica compounds, resulting in true linear regression equations. The graphs of these equations may be seen in Fig. 10 and Fig. 11.

The relationship between linear wear rate and abrasion energy
The logarithm of all data points for the carbon black parametric study and for the silica parametric study was plotted and linear regression equations were generated (Fig. 12). Despite varying the slip rate and load in each study, strong linear trends are observed between the two parameters. Therefore it is observed that the relationship that exists between the two is independent of the test parameters and is more of a function of the abradability of the compound.

Effect of wheel speed on linear wear rate
Multiple wheel speeds were tested in both the “driving” and “braking” direction using the carbon black compound. No difference in linear wear rate was observed between the driving and braking conditions (Fig. 13). This is to be expected as the wear rate is independent from the speed traveled and because the braking and driving conditions differ only in the direction of rotation.

Effect of temperature on linear wear rate
A natural rubber compound was selected for this study to better show any effects from the temperature on the abrasion wear rate. The regression equation and resultant graph (Fig. 14) exhibits an extremely good correlation. However the linear effect of temperature is very small when compared to that of load or slip rate. See Equation 8, where SR is the slip rate and T is the ambient test temperature. Because the formula of the compound tested included the recommended full level of antioxidants, it was desired to test similar compounds with varying levels of antioxidants at high temperature.

Effect of antioxidant levels on linear wear rate at high-temperature abrasion
Three natural rubber compounds were formulated with varying levels of antioxidants; one with no antioxidants, one with the recommended full level, and one with half the recommended amount of antioxidants (Table IV). As expected, the reduced amount of antioxidants lead to an increase in abrasion wear rate, with a higher discrimination apparent at the higher 15 percent slip rate (Fig. 15). It is apparent that the high test temperature condition (60°C) combined with the heat generated by the harsher test condition results in some amount of thermal breakdown in the compounds containing less than ideal amounts of antioxidants.
Weir Minerals releases Isogate valve sleeve series

Weir Minerals, part of the Weir Group P.L.C., has introduced its Isogate WS Series valve sleeves.

The sleeves incorporate Linatex wear-resistant technology and are designed using the company’s experience of slurry knife gate valve applications, according to Weir.

The company said the series extends wear life and improves overall valve performance.

In addition, Weir claims the WS Series valve with its fully interchangeable, one-piece design with integral load distribution rings eliminates the need for multiple pieces and fasteners to make sleeve replacement easier.

Visit www.weirminerals.com for details.

Abrasion

Continued from page 18

The testing of the SSBR-BR carbon black compound (Table 1) resulted in accelerated wear rate at all loads and slip rates on the coarse grain sandpaper, as expected (Fig. 16 and Fig. 17).

The regression equations generated are shown in Equations 9 and 10.

The effect of the sandpaper safety walk roughness on abrasion energy, however, was negligible (Fig. 18 and Fig. 19).

This shows that the abrasion energy required to generate a given slip rate at a specific load is nearly the same for both types of sandpaper, and that abrasion energy is more of a function of the abrasivity of a compound.

The regression equations are shown in Equations 11 and 12.

Summary

The range of talc flow rates applied had no measurable effect on the linear wear rate, proving that it was effective at not allowing the sandpaper to become clogged, and it was not acting as a lubricant.

The slip angle also had no noticeable effects on the linear wear rate or on the abrasion energy under the tested conditions.

It should stand to reason that an applied slip angle should increase both the wear rate and abrasion energy, and so a dedicated study at a low constant slip rate must be performed in order to observe the effects.

As expected, the slip rate and the load applied to the test sample have strong effects on both the linear wear rate and the abrasion energy.

The relationship between the linear wear rate and the applied slip rate is quadratic in nature for both the carbon black and silica compounds under the conditions tested, with accelerated wear occurring at the higher slip rate.

The linear wear rate of the SSBR silica compound was greater than that of the SSBR-BR carbon black compound at all test conditions.

The slip rate and load exhibit strong linear effects on the abrasion energy of both silica and carbon black compounds.

The magnitude of the effects of increasing the slip rate and the load on the abrasion energy was the same for both carbon black and the silica compound.

However, the abrasion energy recorded for the silica compound was greater for every slip rate and load condition tested.

This is most likely primarily because of the characteristics of the polymer systems used, with the effects of the filler being secondary.

There was no difference measured between the “braking” conditions and the “driving” conditions on linear wear rate at similar slip rates.

As expected, there was also no difference in linear wear rate at the different test speeds because the linear wear rate is simply the thickness of rubber abraded per 1000 km.

The effect of temperature on the linear wear rate in a NR compound was linear, yet small in comparison to the effect on slip rate.

And the levels of antioxidants present in the NR compound resulted noticeable differences in the observed linear wear rate when tested.

The compound with the full level of recommended antioxidants showed improved wear compared to the compound with no antioxidants, and the compound with half the level of recommended antioxidants performed nearly halfway between the two.

As expected, the coarse 120 grit sandpaper resulted in accelerated linear wear rate compared to the finer 240 grit sandpaper at all loads and slip rates tested.

The effect of sandpaper roughness on the abrasion energy was negligible, however, indicating abrasion energy is related to the abradability of the compound and not dependent on the track conditions.

Future work includes a temperature study in which NR compounds of varying antioxidant levels will be tested at multiple temperatures.

A dedicated study to examine the effects of increased talc flow will also be conducted. And finally a study to closely examine the effects of slip angle will be performed.

Acknowledgements

The authors acknowledge and thank their colleagues at the Maxxis Technolo- gy Center for their effort and assistance in conducting this study.

Special thanks are extended to Maxxis/Cheng Shin Rubber for permission to publish this paper.